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by

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This paper discusses the potential effects of drilling fluids on semi-enclosed bodies of water such as estuaries. Drilling fluids have been discharged into outer continental shelf waters for many years but there is some concern of potential ecological impact when drilling fluids are discharged near coral reefs or in bays and estuaries. The concern is based on potential adverse effects of the fluids to corals, shellfish, fish, grass beds and general productivity. Potential effects can be evaluated through a hazard assessment process that involves effects and exposure measurements. A suggested hazard assessment involving the Adaptive Environmental Assessment Approach (AEA) is presented. The components of the AEA approach are described and evaluated. In developing the hazard assessment, a review is made of existing effects data. A presentation is made of issues of concern such as resuspension of drilling fluids in shallow, wind-driven estuaries, restriction of light penetration to primary producers by suspended sediments, changes in benthic communities and their substrates, and direct toxicity of the fluids to organisms.

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ABSTRACT

POTENTIAL IMPACT OF DRILLING

FLUIDS ON ESTUARINE PRODUCTIVITY

This paper discusses the potential effects of drilling fluids on semi-enclosed bodies of water such as estuaries. Fluids used in the extraction of oil and gas in off-shore and coastal waters are comprised chiefly of a mixture of barite, water and chemical additives and are pumped into the well through drill pipe and the drill bit. Such fluids serve a number of purposes including cooling the rotary drill bit, lubricating the drill strings and forming a plaster on the sides of the drill hole. Drilling fluids can be discharged directly into receiving waters or they can be removed from the drill site and disposed at sea or terrestrial sites. Drilling fluids have been discharged into outer continental shelf waters for many years but there is some concern of potential ecological impact when drilling fluids are discharged near coral reefs or in bays and estuaries.

The concern is based on potential adverse effects of the fluids to corals, shellfish, fish, grass beds and general productivity. Potential effects can be evaluated through a hazard assessment process that involves effects and exposure measurements. A suggested hazard assessment involving the Adaptive Environmental Assessment Approach (AEA) is presented. The components of the AEA approach are described and evaluated. In developing the hazard assessment, a review is made of existing effects data (exposure assessment data will be evaluated in another paper at this Symposium). A presentation is made of issues of concern such as resuspension of drilling fluids in shallow, wind driven estuaries, restriction of light penetration to primary producers by suspended sediments, changes in benthic communities and their substrates, and direct toxicity of the fluids to organisms.

POTENTIAL IMPACT OF DRILLING FLUIDS ON ESTUARINE PRODUCTIVITY

Man has extracted oil and gas from beneath the sea for many years and recently has become more aware of the potential impact of these operations on marine productivity. In waters contiguous to the United States, exploration and production occurs chiefly on the Outer Continental Shelf (OCS), although these activities also take place to a much lesser extent in more enclosed marine and estuarine areas such as bays. Federal and State regulations now require that an Environmental Impact Statement be prepared to address potential impact of drilling activities on productivity in the area of concern. Also, permits from regulatory agencies to discharge production waters and drilling fluids require consideration of environmental impact.

The environmental data base developed for evaluating and predicting potential fate and effects of drilling fluid on the OCS is useful in evaluating impact of these fluids on estuarine productivity. For example, many of the organisms tested during offshore evaluations were more estuarine than marine. Conversely, models developed to describe the movement of the drilling fluid discharge plume into relatively deep (greater than 20 m) waters of OCS may not be appropriate when the discharge occurs in shallow waters.

The purpose of this paper is to discuss the potential impact of drilling fluids in open marine waters, as evaluated through hazard assessment procedures, and to relate these assessments to estuarine systems. Extensive literature citations and discussions on the impact of drilling fluids on the OCS are available in a review by Neff (1982).

Uses and Composition of Drilling Fluids

Drilling fluids perform several critical tasks in drilling operations. Once regarded only as a medium for transporting drilling cuttings from the well-hole to the surface, these fluids now perform additional important functions (McGlothlin and Klaus, 1980). They cool and lubricate the drill string and bit, maintain cuttings and other solids in suspension during interruptions in drilling, coat the bore with an impermeable cake to prevent fluid loss, reduce corrosion, transmit hydraulic power to the bit and other functions. In order to perform these functions, the drilling muds contain a heterogeneous mixture of chemical and inert ingredients. The exact formulation of a drilling fluid depends upon many factors.

There is no "typical" drilling fluid because the ingredients in a specific fluid depend upon the substrate being drilled, depth of the well and other factors. Some of the basic additives to drilling fluids are shown in Table 1. The relative amounts of the bulk additives and discussion of their properties and relative concentrations are presented by Perricone (1980). Barite, bentonite, lignite and lignosulfate comprise about 90% of the materials used in drilling fluids. Barite, a naturally occurring mineral containing barium sulfate, is used to increase the density of the fluid and is the most commonly used weighting agent. Sodium bentonite, attapulgite and other clays are used to thicken the drilling fluid. Thus, the clays provide viscosity to aid in the removal of drilling fluids from the borehole and improve the wall cake on the borehole. The lignosulfates are used to ensure that the fluid remains "fluid" and does not become too viscous and completely gel. These deflocculants, therefore, permit the use of clays to enhance viscous properties, but avoid the problems of "thick" mud, which include increased fluid pressures, excessive pump pressure and poor bit-cleaning properties. Chrome lignosulfonates are

the most commonly used deflocculants because of their capacity to function at high temperatures and high concentrations of soluble salts.

The U.S. Environmental Protection Agency has specified the following types of drilling fluids to be used in offshore drilling activities in some recent general permits: Seawater/Lignosulfonate, Lime, Nondispersed, Spud, Seawater Gel, Lightly Treated Lignosulfonate, Freshwater/Seawater and Lignosulfonate/ Freshwater. The authorized range in pounds per barrel of components in each of the muds is also specified, as are specialty additives. The type of mud, as well as amounts of components used, varies with well location and substrate characteristics.

Drilling fluids, produced water (those waters that are associated with the oil and gas reservoirs and are produced with the oil and gas) and platform wastes, such as sanitary sewage and platform washings, can be discharged into the marine environment. In general, these discharges are released into seawater in the immediate vicinity of the well. Stipulations are often imposed when the discharge is near areas of special interest, including coral reefs and other biologically sensitive areas. Restrictions exist concerning what materials can be added to drilling fluids as well as discharged. For example, use of bactericides such as pentachlorophenol are prohibited in OCS operations and it is unlawful to discharge into OCS waters fluids contaminated with diesel oil that cause a sheen on the water.

Drilling fluids are discharged intermittently as relatively small-volume discharges or, less frequently, as large-volume bulk discharges. As the fluids are mixed with seawater, they can form two distinct plumes, as indicated in Figure 1. The lower plume contains the bulk of solids and descends rapidly to the bottom, while the upper plume, containing the lighter suspended solids and soluble materials, remains in the water column or drops to the bottom when the

plume collapses some distance from the rig. Obviously, concern about potential impact of drilling fluids must focus on the interface between the fluids in the plumes and biological surfaces in the environment. One method for evaluating this interaction is through a scientific hazard assessment that involves knowledge of environmental concentrations of the fluids and the intensity with which they react with living systems.

Hazard Assessment

Hazard assessment may be defined as a method whereby data are assembled and interpreted to determine potential harm of a substance (e.g., drilling fluids) in the environment. A proper assessment consists of data on duration and intensity of the exposure of organisms to drilling fluids at a specific site. These data are coupled with information on the effects of the fluid on individuals, communities, populations and systems. A stepped sequence of tests to determine environmental concentrations and effects of drilling fluids has been proposed by Richards (1979).

The concept of a stepped sequence or tiered hazard assessment is shown in Figure 1. For this concept to be successful, the information developed for exposure must be integrated with that for effects. Also, research activities in the laboratory and field must be interactive for best results. The end result of the hazard assessment process should estimate the risk of a certain concentration of drilling fluid in relation to toxicity of organisms or systems. Effects studies should progress from simple bioassay tests conducted with indicator organisms to more complicated community and population experiments. The concentrations to be used in these laboratory toxicity tests may be determined through predictive models constructed from laboratory and field data.

Exposure Assessment

Drilling fluids and their components have undergone chemical and physical analyses in the laboratory and on-site studies have followed the transportation and dispersion of drilling fluids released from platforms into the environment. The chemical composition of drilling fluids vary, depending upon the type of fluid being used and the substrate drilled. Trace metals in the fluids are of environmental concern. Analysis of trace metals in drilling fluid is difficult because many of the metals occur as insoluble metal salts. Because of this difficulty and varible purity of barite and other constituents, concentrations of trace metals vary among site-specific fluids.

Chromium, cadmium and mercury are of particular interest because of their acknowledged toxicity and movement through the food web. The valence state of metal species may have a direct effect on toxicity. Chromium chiefly originates from chrome and ferrochrome lignosulfonates. Inorganic chromium salts are added to the fluid when high temperatures are encountered during the drilling process. Chromium is probably complexed with lignosulfonate through various sulfonate and carboxylic acid groups. Soluble chromates (CrVl) are sometimes added during the drilling process and should be reduced rapidly to the more stable trivalent state (Cr 111), according to Moseley (1980). This is of interest because Chromium VI is more toxic and available to organisms than Chromium III. Dr. Thomas Gilbert[1] (personal communication) is concerned that more Chromium VI may be available to organisms from discharged drilling fluids than previously suspected. Gilbert and others are currently involved in research to measure the amount and valence state of chromium in drilling fluids. The amount of cadmium and mercury in drilling fluids depends to a great extent upon the amount of those elements in the barite (Neff, 1980).

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Mercuric sulfide and other metalic sulfides are relatively insoluble and immobile in sediments. However, it is possible for bacteria found in sediments to methylate mercury and cause it to become much more toxic and mobile.

The total organic carbon concentration (TOC) in drilling fluids also varies considerably. Petroleum hydrocarbons may compose 5-10% of the TOC and the hydrocarbons originate from diesel oil or asphalt added during drilling operations or from the strata through which the drilling is proceeding. Diesel oil is sometimes added to lubricate or "spot" the bit to overcome friction between the bit and the strata. Bactericides, such as paraformaldehyde, also account for a small part of the TOC and are added to control bacterial growth, particularly to control breakdown of added starch, in the drill hole. Concentrations of aldehydes in several sump fluids averaged 3 mg/L in a total TOC that ranged from 295 to 10,100 mg/L (Strosher 1980). The use of chlorinated phenols, such as pentachlorophenol, are not permitted in OCS drilling operations.

Transport and Fate of Drilling Fluids

Drilling fluids are released continuously from some drilling operations, intermittently through bulk discharges in others. Some concept of the source or type of discharge and discharge rates from an exploratory well is presented in Table 2. These rates, of course, differ from well to well, depending upon the drilling program. An idealized discharge has been described through a mathematical model by Brandsma et al. (1980) (Figure 2). The model described the heavier particles settling out rather quickly while lighter particles settle much later, after the plume begins to collapse. The very fine particles remain near the surface to form the visible plume. Several field monitoring studies have been performed and models constructed to predict transport of

drilling fluids discharged at various rates and under several environmental conditions. A summary of these studies, prepared by Menzie (1982), is shown in Table 3.

A recent study was conducted to determine the transport of drilling fluids discharged from an exploratory well in the Gulf of Mexico (Ayers et al. 1982). Samples of the plume were taken by divers near the rig and sampling at distances greater than 40 m from the rig was accomplished using a helicopter. Sediment traps were placed from 30 to 200 m downstream and about 3 m above the bottom. Suspended solids were analyzed for aluminum, barium, and chromium by neutron activitation analysis. The drilling fluid used in the experiment was a high density chrome lignosulfonate type. Observations showed that the short-term fate of drilling fluid can be described by a two plume model, an upper plume that contained about 5 to 7 percent of the solids discharged and a lower plume containing cuttings and heavier particles. Concentrations of solids decreased three or four orders of magnitude within 100m downstream of discharge and five to six orders of magnitude at distances from 500 to 1000 m. At 1,000 bbl/hr release rate, transmittance values reached background about 500 m past the point where suspended solids reached background. The transport time for solids to reach background in relation to discharge rate in this study correlated (0.99) with times measured in another off-shore study on Tanner Bank.

Effects of Drilling Fluids

The effects of drilling fluids on marine organisms varies considerably, depending upon the type or component of mud and the species itself. This is

not surprising, given the variability in composition of drilling fluids. In addition, variability in sensitivities of marine organisms is well documented. Much effort has been devoted to developing a data base on the acute toxicity of drilling fluids to marine organisms. However, a paucity of data exists on chronic and community level effects. Some investigators have attempted to characterize the effects of drilling fluids by testing the components of the fluid. Others have subjected test animals to whole fluid samples before the fluid was used ("new" drilling fluid) in the drilling process. A lesser number of used or spent drilling fluids has been tested and there is some question as to the validity of testing new fluids because of the manner in which the chemical and physical properties of the fluids are altered during the drilling process.

The acute toxicity data base compiled by Petrazzuolo (1981) was summarized by Menzie (1982, See in Table 4). A total of 303 tests were reported and the relative frequencies of LC_{50} values occurring within given ranges were calculated. Petrazzuolo reported that the larval forms of shrimp and mysids tested were 3 to 5 times more sensitive than adults and lobster larvae were about 20 times more sensitive. He pointed out an interesting statistical relationship that indicated toxicity was proportional to the square root of the duration time. This relationship is useful in extrapolating from 96-hour LC_{50} values, with the understanding that some difficulties can result from such manipulations (e.g., invertebrates that develop rapidly may be in a more sensitive life stage at 2 hours than at 96 hours).

Much less information is available on chronic and sublethal effects of drilling fluids on marine organisms. Some of these studies were conducted with spent drilling fluids collected from an operating well in Mobile Bay, Alabama. These fluids were barged to an inland disposal site and not intended to be

charged to marine waters. Some consider these fluids "atypical" of fluids released in marine waters (see comments following Rubinstein, et al, 1980), although their effects on invertebrates appear to be similar to those elicited by other spent muds that are discharged in OCS waters (Dr. Ranga Rao,[1] personal communication).

Studies by Rubinstein et al. (1980) and Conklin et al. (1980) with the Mobile muds indicated 17 percent mortality among Mysidopsis bahia, exposed to nominal concentrations of 30 and 100 ppm spent whole mud for 10 days. Six of the fluids were toxic enough to intermolt Palaemonetes pugio to cause 30 to 60 percent mortality in 96 hours at a nominal concentration of 1,000 ppm, one mud causing 100 percent mortality. Nominal concentrations of 10 and 100 ppm caused no mortalities. These drilling fluids also were tested by Derby and Atema (1981) to determine their effect on the American Lobster, Homarus americanus. Lobsters exposed to concentrations of 10 and 100 ppm exhibited impaired response to food odors in 29 and 44 percent, respectively, of the chemosensors examined. Using another spent drilling fluid, Carr et al. (1980) reported that Mysidopsis almyra showed a significant decrease in food assimilation that resulted in reduction in growth when exposed to 10-30 percent of a mud aqueous fraction extracted from 10,000-30,000 ppm mud of drilling fluid.

The impact of drilling fluids on corals has received some attention. Thompson and Bright (1980) and Thompson (1980) found that coral (maintained in the natural environment) and exposed to 100ppm nominal concentrations of used freshwater ferrochrome lignosulfonate retracted their polyps significantly longer than controls. Other studies indicated that the respiration and

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excretion rates of Madracis decactis were not affected by 100 ppm of the Mobile Bay drilling fluids (Krone and Biggs, 1980).

Investigators also have exposed communities of bottom-dwelling macroinvertebrates to drilling fluids in the laboratory and in the field. Macrocosms were employed to observe the effect of drilling fluids on benthic communities that developed from pelagic larvae contained in water flowing through the microcosm (Tagatz et al., 1978, 1980). In one instance, used lignosulfonate fluid was layered over a clean sediment substrate or mixed with the sediment. Drilling fluid/sediment ratios of 1:10 and 1:5 caused a decrease in the number of annelids, particularly Armandia maculata. Rubinstein et al (1980), using Mobile Bay fluids, found molluscs were adversely impacted in nominal concentrations of 100 ppm (in the water column) but their numbers were enriched at lower concentrations tested. These studies did not differentiate between toxic effects and the effects of the drilling fluids physically mixing with and altering the particle size of the sediment substrate. A field study was conducted by Gillfillan et al. (1981), who placed sediment free of organisms and sediment with various percentages of lignosulfonate drilling fluids on the soft bottom of a Maine estuary for 81 days. At the end of the experiment, the trays that contained drilling fluids produced a slightly more diverse community than those with sediment alone. Population density was reduced in sediment that contained 66 and 100 percent drilling fluids.

Observations also have been made of benthic and other communities in the vicinity of drilling rigs. Menzie et al. (1980) observed a zone of drilling mud accumulations near an exploratory drilling rig off the Atlantic coast and found evidence of higher-than-background concentrations of clay 800 m from the rig. He noted some burial of sessile organisms within 150 m of the rig, but this zone yielded an abundance of macrobenthos in certain areas. These

investigators predicted that favorable conditions for benthos recruitment should occur with time. Studies completed near a rig in Cook Inlet, Alaska by Lees and Houghton (1980) were made before, during and after drilling. No statistically significant differences in the benthic populations were noted, although the patchiness of the communities made such studies difficult. Also, relatively high current speed reduced the opportunity for the drilling fluids to accumulate to any extent.

The concept of a sequential, iterative testing program conducted in the laboratory and in the field to develop a hazard assessment is worth pursuing, but often difficult to obtain _in toto_. The literature developed on the fate and effect of drilling fluids serves as an example of this difficulty. A rather large data base on acute toxicity and reports of a few fate studies were developed and published in scientific and nonscientific literature. Petrazzuolo (1981) was the first to make a hazard assessment by bringing together effects and fate data in a Preliminary Report to the Environmental Protection Agency. Scientists, regulators and administrators recently utilized the Adaptive Environmental Assessment (AEA) approach to develop an assessment (Auble et al. 1982) and results of the workshop generally agreed with Petrazzuolo's (1981) work.

The Adaptive Environmental Assessment method was developed by scientists at the International Institute for Applied Systems Analysis in Austria and the University of British Columbia. This methodology has been successfully used at the beginning of research projects to formulate a research plan and after a data base has been established to synthesize existing data and to point out weaknesses or data gaps. The synthesizing aspect of the method was applied to drilling fluids when representives from industry, academia and government met for a 5-day workshop to discuss the potential impact of drilling fluids on the marine environment.

The focus of the workshop was construction and refinement of a quantitative, dynamic, simulation model to describe the impact of drilling fluids on the environment. Obviously, models developed in five days (even with some pre-workshop activity) are preliminary and will require modification and refinement. But the methodology of AEA is such that the process of building this preliminary model is more important than the model itself. Development of the model permitted participants to focus on the issues and data at hand, even though they may differ in their approach to the problem. The processes also require participants to take a more holistic view of the question of impact and promote interdisciplinary communication. Those developing toxicity data had to talk with those estimating environmental concentrations. The model requires rather explict data, so participants were as precise as possible with their input. Since this method may be pertinent to estuarine productivity studies, much of the following information is presented directly from the workshop report.

The analysis of impact began by simplifying the system to a representation detailed enough to satisfy concerns of the participants. Simplification or "bounding" was accomplished by describing management alternatives, identifying measures to evaluate effects of the alternatives and defining reasonable spatial and temporal frameworks. Management alternatives included altering discharge depth and rate, predilution and altering mud composition. Indicators included concentration of suspended solids, mortality rates within the plume, population size, growth rate and bioaccumulation. It was decided that a specific geographical location was inappropriate, so a hypothetical drilling operation in open waters of the Gulf of Mexico was chosen for the model structure. The drilling fluid discharge plume in the water column was represented by a set of plume-slice intervals, each representing 1 minute of

discharge. On the bottom, environmental effects in 1-m^2 areas at five distances downstream were established. A time horizon of 20-30 years was selected for this model. Incremental time steps varied from one minute in the water column to one month elsewhere.

The following major components or sub-models were designated by the workshop participants:

(a) Discharge/fate - characteristics of discharge plume and fate of materials in the plume,

(b) Water-Column Effects - impact of discharge on zooplankton in upper plume,

(c) Soft-Bottom Effects - effects of discharge on microbes, meiofauna, and macrofauna,

(d) Hard-Bottom Effects - response of coral to exposure to drilling muds and cuttings.

An additional sub-group considered at the same time the impact of drilling fluids on enclosed or semi-enclosed bodies of water, such as bays and estuaries. They did not build a model, but did focus on variables that would differ between open and closed areas.

After the submodels were developed, linkages between the submodels were defined. This required that each subgroup identify what they needed from the others in order to develop specific sub-models.

Discharge/Fate

The discharge/fate submodel was constructed to consider indicators of interest, which included discharge frequency and duration, and associated plume size, dispersion ratios, concentrations of soluble and solid fractions at different distances from the platform, and both the depth of sediment added and fraction of whole mud in sediments at different distances as model variables.

Variations in discharge rate and amount and predilution were also included. The discharge was conceptualized as separating into an upper plume containing liquid fractions, as well as fine clay and other particles, and a lower plume containing most other discharged materials. The upper plume was considered to be 20 m thick spreading at an angle of 53° for the first 10 min of transport time and constant width thereafter. The plume was assumed to be at a depth of neutral bouyancy specified for each model run. These characteristics represented actual observations of plumes made in the field and also represent an empirical alternative to the complex mathematics required to model convective descent, dynamic collapse and passive diffusion phase of a plume described by Brandsma et al. (1980).

Dispersion ratios, the ratio of suspended solids in discharge to suspended solids in upper plume, were calculated from a multiple regression, using transport time and the inverse of discharge rates as independent variables:

$$\underline{DISP} = 10^{4.4495} * (1/DISCHR)^{0.35674} * (TT)^{1.1001}$$

where $\underline{DISP}$ = Dispersion Ration

$\underline{DISCHR}$ = Discharge Rate (bbl/hr)

$\underline{TT}$ = Transport Time (min)

This regression was based on observed dispersion ratios from three wells summarized by Petrazzuolo (1981). The squared correlation coefficient ($\underline{R^2}$) for this regression was 0.74.

Plume volume, dilution factor for upper plume, and dispersion ratios for solid fractions were calculated by the model, assuming a 10 m/min current and total discharge of 600 bbl. Sediment build-up on the bottom was also calculated and adjusted for storm surges.

Although the discharge/fate submodel provided reasonable plume characteristics for use of the other submodels, it lacked explicit mathematical

treatment of detailed physical and chemical plume characteristics and some environmental variability.

Water Column Effects Submodel

This model used an estimate of the proportion of water column planktonic organisms within the plume that could be killed by single discharge as an indication of the health of the water column. Zooplankton mortality in the plume was used to estimate percentage loss in monthly recruitment of larval forms to the benthos.

The shape and characteristics of the plume supplied by the discharge/fate submodel was divided into slices, each representing 1 minute's discharge. The concentration of an organism's exposure in a given plume would decrease with time because it was assumed that animals entrained at any point would be carried by the same currents moving the plume and thus beexposed to a declining concentration gradient.

The model was used to compute average concentration (C_{st}) for the period of exposure (t) of each subpopulation

$$C_{st} = \frac{\sum_{i=s}^{s+(d-t)} c(i)}{(d-t+1)}$$

where $\underline{c}\ \underline{s}\ \underline{t}$ = mean exposure concentration for organisms entering slice "$\underline{s}$" at time "$\underline{t}$" (where t=1 is first minute of discharge)

$\underline{c(i)}$ = concentration of solubles (ppm) in slice "1"

$\underline{d}$ = total duration of discharge (min)

Following Petrazzuolo (1981), an LC_{50} value appropriate to each subpopulation's "$\underline{t}$" minutes of exposure was estimated thusly:

$$\text{t-min } LC_{50} = \text{96-hr } LC_{50} \times \left(\frac{96\text{hr}}{\text{tmin}} \times \frac{60\text{min}}{\text{hr}}\right)1/2$$

Using these values, one can obtain a graphical interpretation of this portion of the hazard assessment. The graph in Figure 3 indicates the projected environmental concentration of drilling fluids with time and the toxicity of this concentration at time "t", considering 96-hr LC_{50}s of 50 and 100 ppm. These theoretical values give some idea of the manner in which the model output can be used. In this instance, the toxicity curve does not cross or even approach the exposure concentration curve; therefore, this specific set of circumstances would not be considered hazardous.

Total plume mortality and potential monthly recruitment losses were calculated from a 50 ppm LC_{50} value and concentration of drilling fluid at time t where t was considered to be 120 min.

$$R\ LOSS = \frac{NDIS \times DDIS \times TPM}{30\ (days/month) \times 24\ (hrs/day) \times K}$$

where NDIS = number of discharges per month

DDIS = duration of discharge and post discharge phase (hr)

TPM = total plume mortality rate

$$K = \frac{\text{depth of water column}}{\text{depth of plume}}$$

Calculations indicate that even with 100% mortality in the plume, monthly reduction in potential benthic recruitments would be small.

The major limitation to this model is the extrapolation of 96-hr LC_{50} toxicity data obtained in the laboratory at constant concentration to toxicity of organisms exposed to decreasing concentrations in the field. In the model, LC_{50} for shorter time-periods would be increased by a factor equal to the square root of the relative exposure time.

Soft Bottom Effects Submodel

Construction of this submodel required considerable simplification of complex biological processes and can be considered a rather general conceptual model. A basic assumption was that soft bottom areas in the Gulf of Mexico are subjected to frequent storm events. Thus, community was then chiefly composed of "invader" species characterized by rapid recovery and colonization. The submodel dealt with bioaccumulation, survival and sublethal response of four indicator groups.

Bioaccumulation of chromium from bottom sediments was related to the fraction of whole drilling mud resulting from discharge. Oyster flushing rates were used to account for the benthos' ability to flush excess chromium from their tissue. Predictions of chromium content of epifaunal tissues indicated that 0.04 fraction of whole drilling mud in the sediment would yield tissue concentrations of about 8 ppm, and 0.08, in about 35 ppm.

Mortality was caused by burial by discharged mud, toxicity of the mud and by removal of deposited sediments by storms. Population changes due to storm intensity were indexed according to the amount of sediment removed by each storm. The model indicated that 0.04 fraction of whole mud in sediment will result in about a 0.60 survival rate and 0.08 will cause about a 0.20 survival rate. Monthly survival rate will be reduced to 0.50 by 150 cm depth overlay. Population recovery, as colonization, was affected by such factors as depth of deposited sediment, fraction of whole mud and re-establishment of oxygenated layer. A plot of the fraction of first-month potential recolonization due to toxicity of residual muds (indicated by fraction of whole mud in the sediment) showed that 0.010 fractions whole mud would permit about 0.78 of the community recolonizing.

Limits of this model include overemphasizing the "invader" species concept and their resistance to burial. Also, the lack of consideration of interdependence among faunal groups and the need to use short-term toxicity data to predict long-term effects may cause over- or under-estimates of effects.

Hard-Bottom Effects Model

The hard bottom model uses the impact of drilling fluids on corals as a indicator organisms because of the lack of data on other organisms, such as sponges and gorgonians. Coral were considered as individuals, rather than the entire reef community. Uncertainty in four major impacts of fluids on corals, mortality due to sediment deposition, direct mortality due to plume toxicity; reduced growth due to plume toxicity, and reduced recruitments due to burial of appropriate substrates were resolved in favor of a worst-case basis. Biomass dynamics of the coral were represented by the following equation:

$$C_t = 1 = C_t - SC_t - PC_t + G + R$$

where $\underline{C}$ = coral mass

$\underline{S}$ = mortality

$\underline{P}$ = mortality due to toxic plume (%)

$\underline{G}$ = growth (gC/m^2)

$\underline{R}$ = recruitment (g/Cm^2)

Survival rates were calculated as a function of depth and indicated 0.50 survival rate at 2 cm depth of sediment coverage and 0.25 rate at about 2.5 cm depth. Monthly survival rate of 0.50 occurred at about 900 ppm suspended solids and 0.25 survival at about 1200 ppm. The growth rate of coral was reduced approximately 85 percent where exposed to 100 ppm suspended material.

Limitations of the model include the lack of factors relating the interaction of corals with the coral community and extrapolation of 96-hr LC_{50} data to shorter time intervals.

Systems Models

The four submodels were utilized to produce holistic output in the following manner: For each monthly iteration, the discharge/fate submodel calculated upper plume characteristics and deposition of drilling muds and cuttings; the water column submodel next calculated impacts of the upper plume on zooplankton and benthic recruitment, and the soft and hard bottom submodels then calculated potential impact.

The sample outputs shown in Table 5 are presented as approximate maximum values. These terms may be misleading in that participants in the workshop considered these models valuable in addressing semi-quantitative changes and trends, not in terms of absolute numbers. The numbers represent only a point from which discussions can take place and the limits of applicability of the models to actual field conditions can be determined.

Bays and Estuarines

Much of the data and discussions developed for offshore areas are applicable to enclosed bodies of water, such as bays and estuaries; however, some characteristics of "enclosed" areas preclude this simple extrapolation. Participants of the AEA work shop (Auble et al., 1982) suggested that the following modifications of their models representing open waters would be needed in order to adapt them to estuarine areas:

(1) Additional communities, such as aquatic macrophytes and oyster beds, would have to be treated.

(2) The importance of "closed" water bodies as food production and rearing areas would necessitate more detailed incorporation of population-

level processes and trophic interactions.

(3) Many of the processes represented in the open water simulation model, such as plume dynamics, sediment deposition, and sediment redistribution, would require fundamentally different mathematical treatment due to shallower water and more complex circulation and stratification patterns.

(4) The importance of resuspension in shallower water and slower long-term dispersion would necessitate more detailed consideration of long-term effects of slightly elevated concentrations.

Some complications encountered when describing the impact of drilling fluids on estuarine areas are due to the great variability in estuaries. For modeling purposes, open ocean systems are more similar to each other and less complicated than estuarine systems. Salinity patterns differ greatly among estuaries; circulation, even general patterns, also differ. The effect of wind-driven currents and tidal currents differs because the shape and depth of the basins forming estuaries differ. Resuspension of bottom particles must be of more concern in estuaries because wind-driven currents stir the bottom and cause continuous resuspension of deposits.

Drilling fluids could indirectly impact aquatic macrophytes that occur in the shallower areas by interfering with penetration of sunlight to the plants and directly by burying the plants or by toxicity. For instance, the effect of a kraft mill waste on seagrass beds in Florida was partly attributed to altered light penetrability due to the presence of suspended particles in the wastes (Zimmerman and Livingston, 1976.) Both transplanted and indigenous seagrasses in Red Fish Bay, Texas were debilitated by sediment accumulation from a dredging project, followed by a colder than normal winter (Phillips, 1980). The plants were subjected to dredged sediment from 15 to 25 cm deep. Sediment deposition rates of 5 cm per month exceed the growth rate of the seagrass

Halodule in the Mississippi Sound, according to Eleuterius (1974), and deposition caused the plants to die.

Another area of concern is the possibility that drilling fluids will mix with existing sediment, alter the particle size (thus, the texture) of the sediment and adversely affect the suitability of the sediment for settling organisms, such as clams, oysters, scallops and other macrobenthos. Texture and other characteristics of bottom sediment are critical in determining whether planktonic larvae will select a particular substrate (Thorson, 1966). The avoidance of a particular substrate could be critical at certain lifestages of the pelagic larvae and could lead to decreases in populations of commercial fishery organisms as well as polychaets and other important food organisms. The degree to which drilling fluids could alter a substrate depends upon variance in particle size distribution in the fluid and existing substrate and, of course, would require transport of the fluid in sufficient quantities to cause significant alteration of sediment texture. Consequently, the modeling of effects in these inshore areas would be more complex than for offshore conditions.

Summary and Recommendations

Several investigators have assembled data available on the effects and environmental concentrations of drilling fluids in the marine environment and made predictions about potential impact. Petrazzuolo (1981) concluded that effects of drilling fluids released in the water column would not be substantial. Participants of the AEA Workshop (Auble et al, 1981) arrived at the same conclusion based on the "first-cut" models. Benthic organisms near the well could suffer high reduction in numbers, while those from 185 - 1400 m would suffer 2-10% reduction, according to Petrazzuolo (1981). The benthic impact was based on extrapolation of toxicity data as well as recruitment

and development in a flow-through test system.

The assessments to date are based on effects data derived chiefly from estuarine and near-shore organisms and transport and fate data from discharges of off-shore wells into relatively deep water. Models should be developed that will more realistically estimate impact on productivity of shallow, highly spacial and temporally variable estuarine systems. This includes consideration of bottom-dwelling plants, including seagrasses and their attendant communities, as well as chronic effect studies with variable exposure scenarios. Transport and fate (exposure) models must deal with depths from 3 to 20 m, resuspension of particles due to wind-driven currents and more emphasis on potential alteration of substrate texture. Fortunately, much has already been learned about drilling fluids that is applicable to these considerations, but some estuarine-oriented research is required before a realistic hazard assessment can be made for this productive part of our environment.

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TABLE 1

SOME CHEMICAL INGREDIENTS IN DRILLING MUD

Ingredient	Use
Barite Bentonite Attapulgite	Weighing Agents and Viscosifiers
Sodium Tetraphosphate Modified Tannin Chromium Lignosulfonate Calcium Lignosulfonate Lignite	Dispersants and Thinners
Starch Cellulose	Fluid Loss Reducers
Detergents Non-Ionic Emulsifier Processed Hydrocarbons including Diesel Oil	Lubricants and Emulsifiers
Aluminum Stearate, Octyl Alcohol Paraformaldehyde	Defoamers Bactericides and Speciality Items
Sodium Chromate Sodium Hydroxide Potassium Hydroxide	Corrosion Inhibitor pH Control pH Stability

Table 2. Summary of drilling fluid discharges from the Ocean Ranger From Houghton et al., 1980.

Type of Discharge	Volumetric Composition	Discharge Frequency	Discharge Rate	Flushing Water
Shakers	50% Cuttings 7.5% Dry Mud Components	Continuous while drilling	1-2 bbl/hr	470 bbl/hr[a]
Desander	25% Sand 75% Water	2-3 hr/day while drilling	3 bbl/hr	10 bbl/hr[a]
Desilter	22.5% Silt 2.5% Dry Mud Components 75% Water	2-3 hr/day while drilling	16-17 bbl/hr	40 bbl/hr[a]
Centrifuge	1% Dry Mud Components 99% Water	1-3 hr as required	30 bbl hr	4 bbl/hr
Sand Trap	20.0% Sand 7.5% Dry Mud Components 72.5% Water	Every 2-3[b] days	88 bbl in 2-10 min	520 bbl/hr
Sample Trap	15% Dry Mud Components Cuttings 85% Water	Every 2-3[b] days 5-10	15 bbl/hr 5-10 min	520 bbl/hr
Dilution to Control Rheology	10-15% Dry Mud Components 85-90% Water	Less than 3 per well	700 bbl/hr (max. 200 bbl)	520 bbl/hr
Cementing	10-15% Dry Mud Components 85-90% Water	3-6 Times[b] per well	10 bbl/min for up to 20 min	520 bbl/hr
End of Well	10-15% Dry Mud Components 85-90% Water	Once per well[b]	700 bbl/hr	520 bbl/hr

a = flushing water is run continuously.
b = not discharged while drilling.

Table 3. Characteristics of field monitoring studies designed to examine the fate and effects of drilling discharges Menzie (1982).

Type of Study	General Sampling Methodology	References
Water column studies	Plume dispersion monitoring Hydrographic sampling from helicopters Dye tracers Acoustic monitoring	Ayers et al. (1980a, b); Meek and Ray (1980); Houghton et al. (1980); Proni et al. (1980);
Sediment trap studies	Helicopter or vessel deployed sediment traps at various depths and distances from the well site	EG&G (1980); Meek and Ray (1980); Ayers et al. (1980b); Dames Moore (1980)
Benthic studies Visual physical alterations	UTV, Side-Scan Sonar, bottom photographs, divers, visual analysis of cores	EG&G (1980); Menzie et al. (1980); Gillmor et al. (1981); Zingula (1975); Lees and Houghton (1980)
Physical and chemical alterations of sediments	Grabs and cores from sediment around well site. Generally analyses of upper few cm	Mariani et al. (1980); EG&G (1982); Union Oil Company (1977); Mobile Oil Corp. (1978); CSA (1979) Meek and Ray (1980); Lee and Houghton (1980)
Bioaccumulation of trace metals in benthic fauna	Collections of grab samples and sieve for fauna	Mariani et al. (1980); Crippen et al. (9180); EG&G (1982)
Abundance and compositions of infauna and epifauna	UTV, bottom photographs, trawls, benthic grabs	Menzie et al. (1980); Gillmor et al. (1981), and in press); Lees and Houghton (1980); Crippen et al. (1980); EG&G (1980)

TABLE 4

SUMMARY OF THE ACUTE LETHAL TOXICITY DATA FOR DRILLING FLUIDS Menzie, 1982

	Number of species tested	Number of fluids tested	Number of tests	Not determinable	Number of 96-h LC_{50} values (ppm)*				
					100	100-999	1000-9999	10 000-99 999	100 000
Plankton	1	9	12	5	0	0	7	0	0
Invertebrates									
Copepods	1	9	11	1	0	3	5	2	0
Isopods	2	4	6	0	0	0	0	1	5
Amphipods	4	8	19	0	0	0	0	5	14
Gastropods	5	5	10	0	0	0	0	2	8
Decapods									
Shrimp	7	16	48	0	0	5(0)[b]	0	27	17
Crab	3	12	24	1	0	0	0	11	12
Lobster	1	2	7	0	0	0	1	3	3
Bivalves	7	14	33	0	0	0	1	15	17
Echinoderms	1	2	4	0	0	0	0	1	3
Mysids	3	9	24	1	0	0	0	14	9
Polychaetes	4	14	22	0	0	0	0	4	18
Finfish	11	25	83	0	0	0	2	47	34
Totals	48	40[c]	303	8	0	8	16	132	140
Percentages as a fraction of the number of tests				2.5%	0%	2.5%[b] (1%)	5%	44%	46%
Average percentages, based on the percentage values for each of the above 13 groups of animals tested				5.3%	0%	2.8%[b] (2.1%)	9.4%	33%	50%

[a]Placement in classes according to: (a)LC_{50} value, (b) lowest boundary of range if LC_{50} expressed as a range, (c) cited values if given as ">" or "<". There were 119 such LC_{50} values: 95 were >100 000 ppm; 20 were >10 000 ppm; one was <50 000 ppm; two were <20 000 ppm; one was <3200 ppm.

[b]These include tests conducted on drilling fluids obtained from Mobile Bay, Ala., which may not be representative of drilling fluids used and discharged on the OCS. Values in parentheses exclude data from the Mobile Bay mud tests.

[c]The fluids used in Gerber et al., 1980, Neff et al., 1980, and Carr et al., 1980, were all supplied by API. Characteristics have similar and may have been subsamples of the same fluids. If so, the total number of fluids tested would be 35. Source: Petrazzuolo, 1981.

Table 5

SYSTEM MODEL SCENARIOS

SCENARIO	TYPE PLATFORM	VARIABLE					SAMPLE OUTPUTS (ARRPOXIMATE MAXIMUM VALUES)								
		Depth of Water (m)	Discharge Rate	Total Discharge (m tons)	Time (yrs)	Maximum Depth of Deposit of Spent Muds	Fraction Whole Mud In Sediment			Conc Suspended Sediments In Upper Plume (ppm)			Coral Biomass (GC/m^2)		
							50	100	500	50	100	500m	50	100	500
I	Production	80	600 BBL every 3 days 1000 BBL/HR	1500	20 yrs (Drilling beginning in 1st ending in 3rd yr)	15 cm in 154 m circular area	0.12	.09 (3 yrs)	.02	58	28 (3 yrs)	5	0	0 (5 yrs)	90
II	Same as I	80	600 BBL every 3 days 30 BBL/HR	1500	20	15 cm in 154 m circular area	0.12	.09	.02	20	9	1.5	0	0	90
III	Same as I	20	600 BBL every 3 days 1000 BBL/HR	1500	20	34 cm - 33 m circular area	0.16	0.12	0.02	58	28	5	90	60	50
IV	Same as I	20	600 BBL every 3 days 30 BBL/HR	1500	20	34 cm - 33 m circular area	0.16	0.12	0.02	20	9	1.5	0	0	50

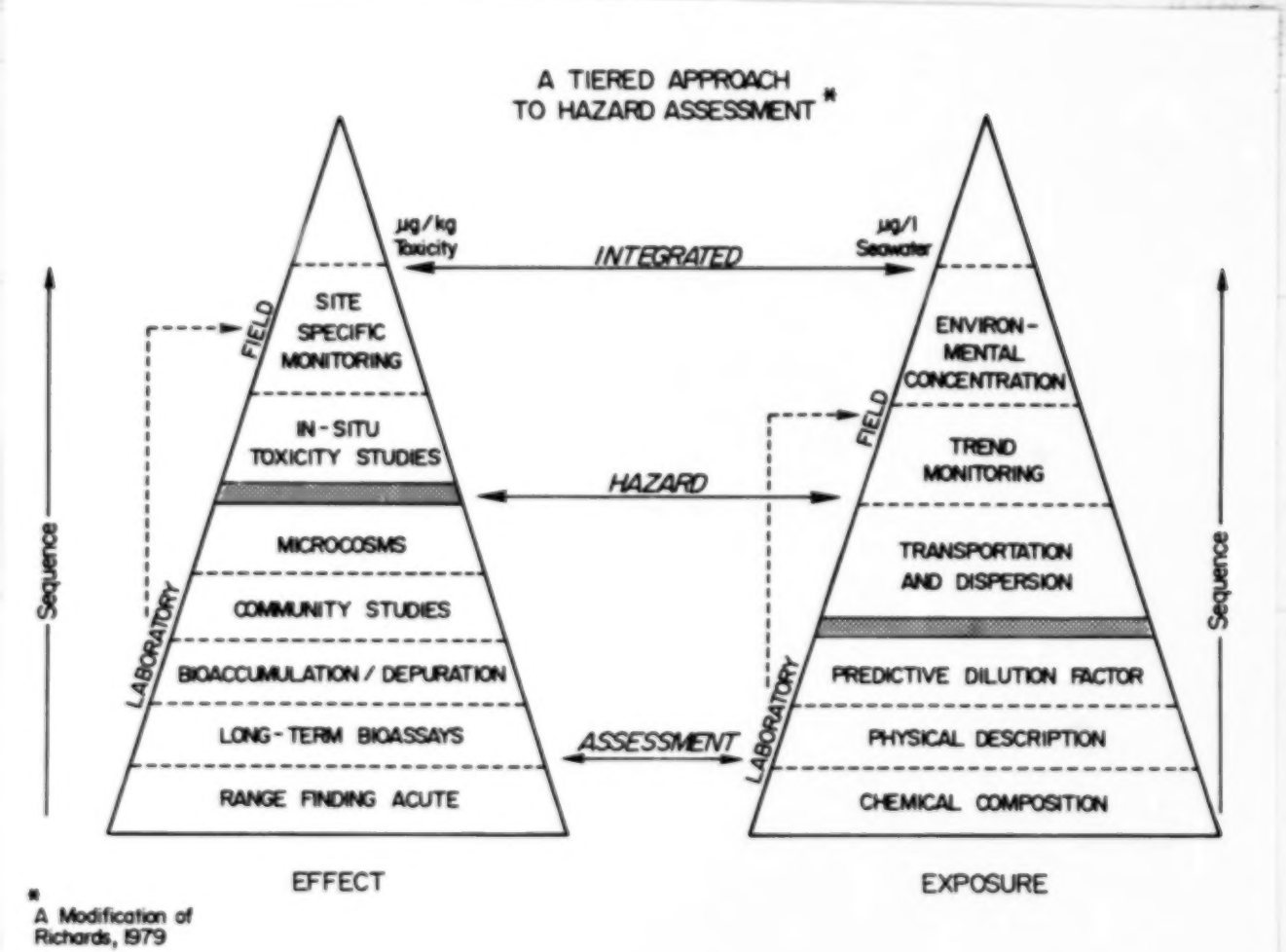

Figure 1. A Tiered Approach to Hazard Assessment
(Modification of Richards, 1979).

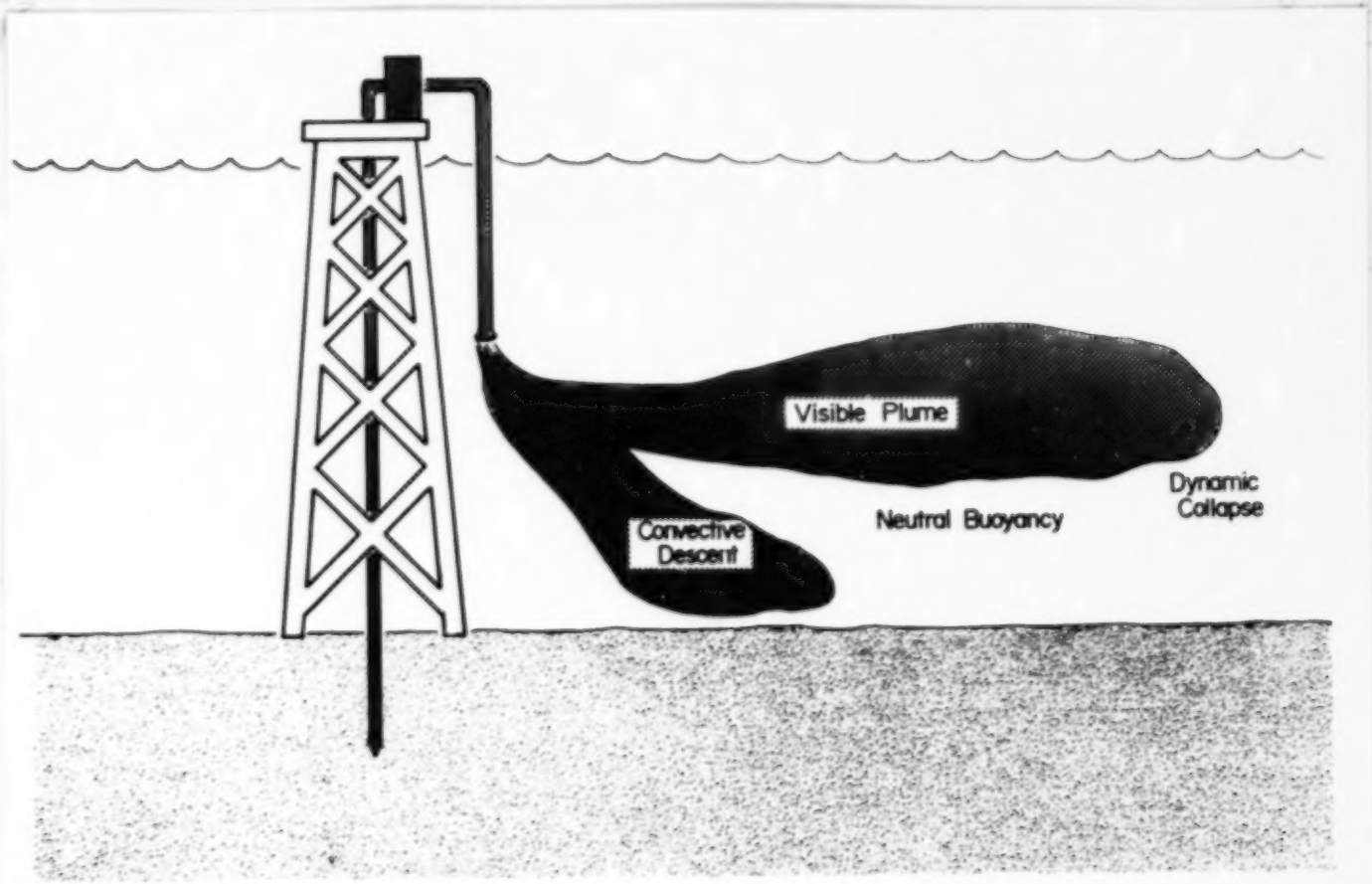

Figure 2. Idealized Disharge of Drilling Fluids into Outer Continental Shelf (Modification of Brandsma, 1980).

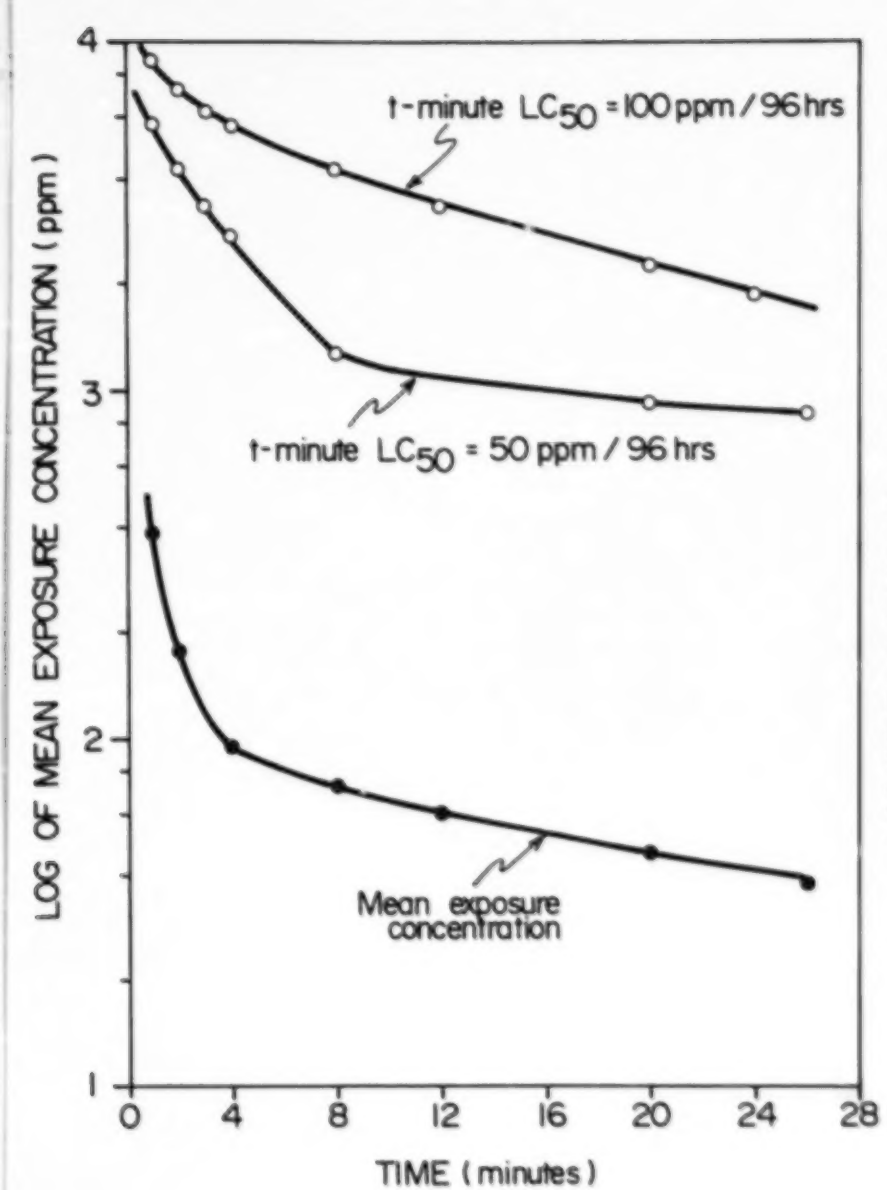

Figure 3. Comparison of Predicted Concentration of Drilling Fluid with Theoretical LC-50 values with Time.